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Overview of Point Spread Function of Seawater

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14. ABSTRACT
The point spread function (PSF) describes response of a linear optical imaging system to a point light source (see Point spread function and imaging in turbid medium). This response includes the effects of both the image system itself (lens, mirror, recording media, etc.) and of the medium the optical signal passes through (for example, seawater). By using the concept of the PSF, closely related to BSF, effects of different components of such a linear system can be separately modeled and multiplicatively accounted for in the spatial frequency domain. Mathematically, an image, g(x, y), of an object is the combination of the original signal (image), f (x, y), convolved with the PSF of the entire imaging system, h(x, y), and of the noise, n(x, y):

$g(x, y) = f(x, y) * h(x, y) + n(x, y)$

where coordinates x, y indicate a position in the image and the symbol * denotes the operation of convolution. If the PSF is shift invariant, the convolution of f and h in the spatial domain corresponds to a simple multiplication of the Fourier transforms, fF and gF, of f and h, respectively. This is referred to as the convolution theorem (for example http://mathworld.wolfram.com/ConvolutionTheorem.html).

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Point and beam spread functions of seawater

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Fig. 1, Fig. 2

The point spread function (PSF) describes response of a linear optical imaging system to a point light source (see *Point spread function and imaging in turbid medium*). This response includes the effects of both the image system itself (lens, mirror, recording media, etc.) and of the medium the optical signal passes through (for example, seawater). By using the concept of the PSF, closely related to BSF, effects of different components of such a linear system can be separately modeled and multiplicatively accounted for in the spatial frequency domain. Mathematically, an image, $g(x, y)$, of an object is the combination of the original signal (image), $f(x, y)$, convolved with the PSF of the entire imaging system, $h(x, y)$, and of the noise, $n(x, y)$:

$$g(x, y) = f(x, y) * h(x, y) + n(x, y) \tag{1}$$

where coordinates x, y indicate a position in the image and the symbol * denotes the operation of convolution. If the PSF is shift invariant, the convolution of f and h in the spatial domain corresponds to a simple multiplication of the Fourier transforms, f_F and g_F, of f and h, respectively. This is referred to as the convolution theorem (for example http://mathworld.wolfram.com/ConvolutionTheorem.html).

An accurate PSF model of the seawater is essential in understanding the image formation and restoration processes for a linear system (Hou W et al 2008, 2007a).

The PSF and BSF of a turbid medium, closely related to each other, both depend on several optical properties of that medium, such as the scattering phase function (SPF), the scattering coefficient, b, and the beam attenuation coefficient, c. While these latter properties inherently refer to single scattering of light, both the PSF and BSF of the medium account for all orders of scattering (single and multiple scattering).

A relationship between the SPF and PSF can be obtained by Monte Carlo (MC) simulations (Hou W et al 2008, Jaffe JS 1995), which can serve as a benchmark for other theoretical or empirical approaches when measured SPFs (or closely related VSFs) are used to determine the fate of an energy packet in the MC simulation process.

The most thorough empirical relationship to-date between optical properties of seawater and the BSF is that obtained by Duntley SQ 1971, who reported extensive laboratory measurements of the BSF. Duntley's measurements, performed on simulated ocean waters with a wide range of optical thicknesses (τ = 0.5 to 21) can be summarized as follows:

$$BSF(\theta) = \frac{E(\theta)}{P_0} = \frac{10^{A - C\,\theta^{B}}}{2\pi \sin\theta} \tag{2}$$

where E is the irradiance, θ is the scattering angle, and P_0 is the incident beam power. A, B, C are parameters dependent of the optical thickness (τ) and the single scattering albedo (ω_0). The formulas for parameters of A, B, C are cited in Hou W et al 2008 (p. 9960). However, the formulation of Duntley does not have a flexibility to work with different water-types, because only two parameters (τ, ω_0) were used.

Simplicity of a PSF model can be beneficial when per-pixel calculations are needed in such applications as a high-resolution scene simulation or real-time image processing. Hence, Voss KJ 1991 suggested a simpler empirical form that fitted PSFs of three different types of waters with errors under 14% (the Sargasso Sea, Tongue of the Ocean at the Bahamas, and coastal Pacific Ocean):

$$PSF(\theta) = p\,\theta^{-q} \tag{3}$$

where p and q are constants. Unfortunately, this form lacks explicit relationships to the optical properties of seawater referred to earlier in this note. The values of q determined by Voss KJ 1991, for θ ranging from 4 to 100 mrad, varied between 0.4 to 2.0 when the optical thickness varied between $\tau = 0$ to 10.

Hou W et al 2008 formulated a semi-empirical relationship between the PSF and the optical thickness, τ, single scattering albedo, ω_0, and the mean scattering angle, θ_0:

$$PSF(\theta) = K(\theta_0)\,\frac{\omega_0\,\tau\,e^{-\tau}}{2\pi\,\theta^{n}} \tag{4}$$

where K is a constant, and $n = 1 / \omega_0 - 2\tau\theta_0$. The authors, who also compared their approach with other analytical and numerical PSF models, showed that the above relationship remained valid up to an optical thickness of 15 when compared to Duntley's model (Duntley SQ 1971). They also showed that the parameter θ_0 in their formulation is capable of compensating for differences between Duntley's model and the field measurements of McLean JW and Voss 1991.

By assuming an integrable form of the SPF and using the small-angle scattering approximation (see *Small-angle approximation to the radiative transfer equation: Introduction*), one can derive exact analytical BSF (Fournier GR and Jonasz 1999), or its Fourier transform, the modulation transfer function (MTF) (Mertens LE and Replogle 1977, Wells WH 1973, see also *Small-angle approximation to the RTE with application to ocean waters*). A different approach was used by Dolin LS et al 2006, who applied numerical approximations in their analytical formulation of the PSF. The model proposed by Hou W et al 2008 closely matches both Monte Carlo simulations based on empirical data for the seawater VSF as well as analytical and numerical models cited here (Figure 1, Figure 2).

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